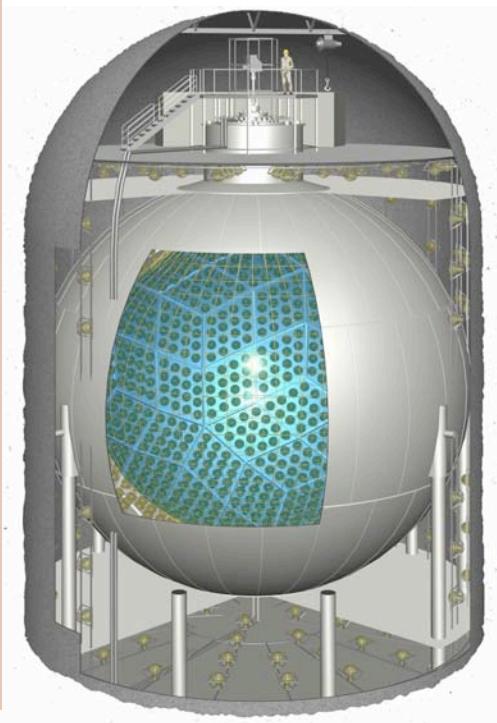
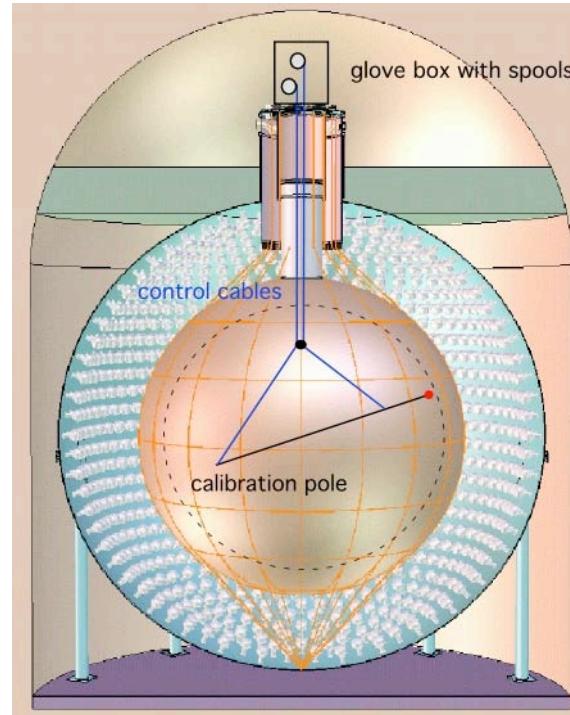
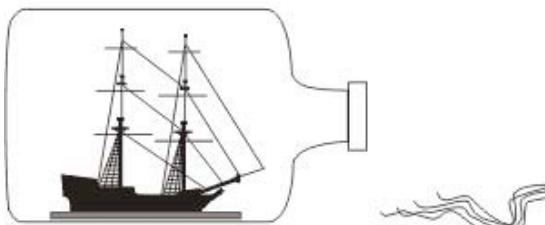
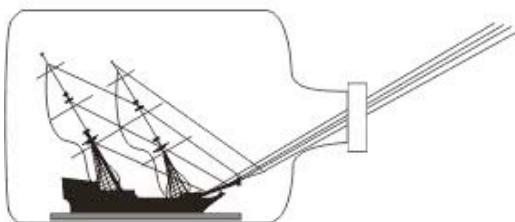
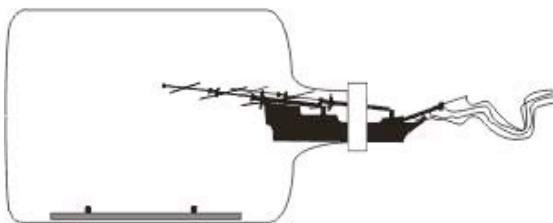
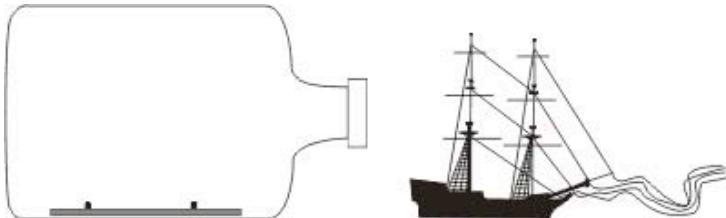




# Full-Volume Calibration in KamLAND

## The System and its Physics Potential

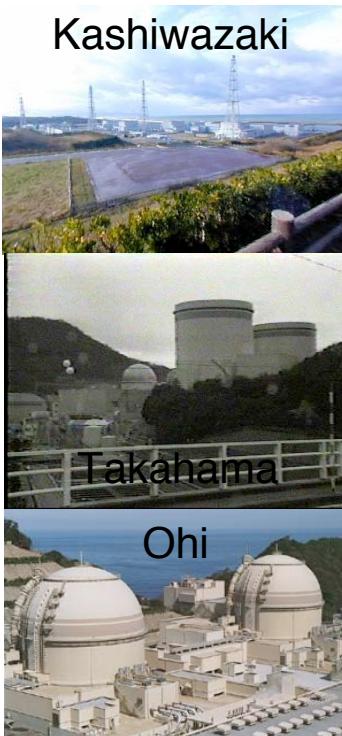


Karsten M. Heeger, LBNL

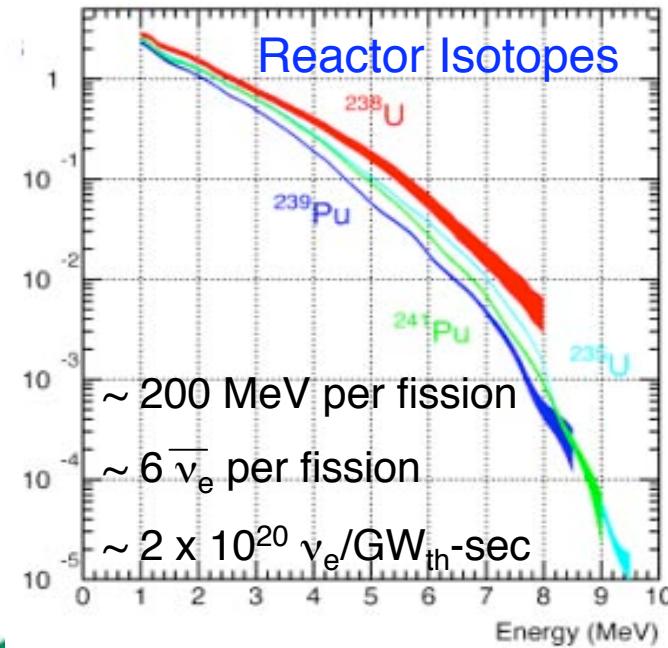
*for the KamLAND Collaboration*

# Measurement of Reactor Anti-Neutrinos in KamLAND

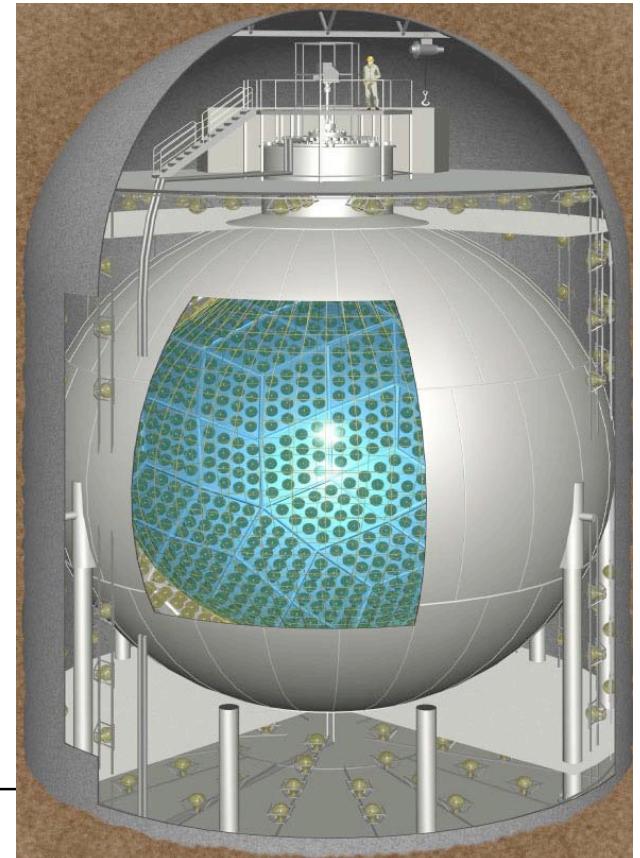
## Japanese Reactors



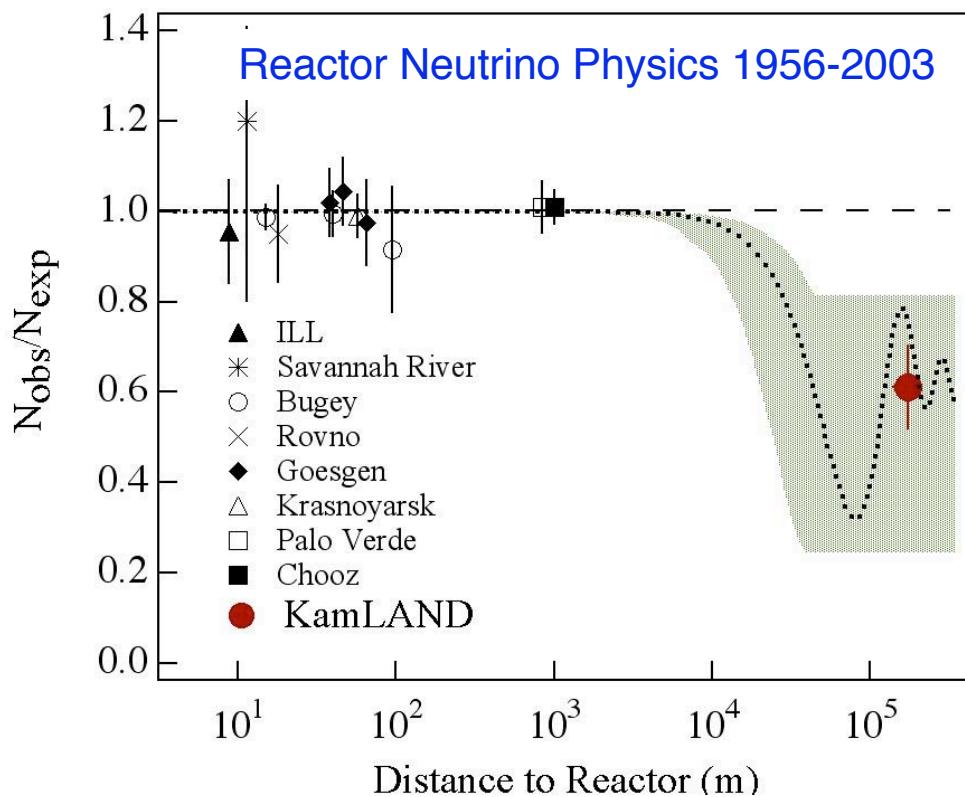
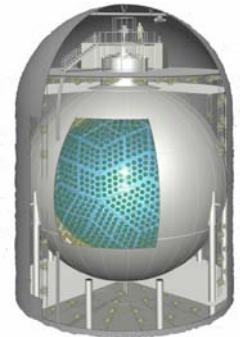
53 reactors



Anti-Neutrino Detection  
through inverse  $\beta$ -decay



# KamLAND in 2003: First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance



PRL 90:021802 (2003)

Observed $\bar{\nu}_e$	54 events
No-Oscillation	$86.8 \pm 5.6$ events
Background	$1 \pm 1$ events
Livetime:	162.1 ton-yr



Japan

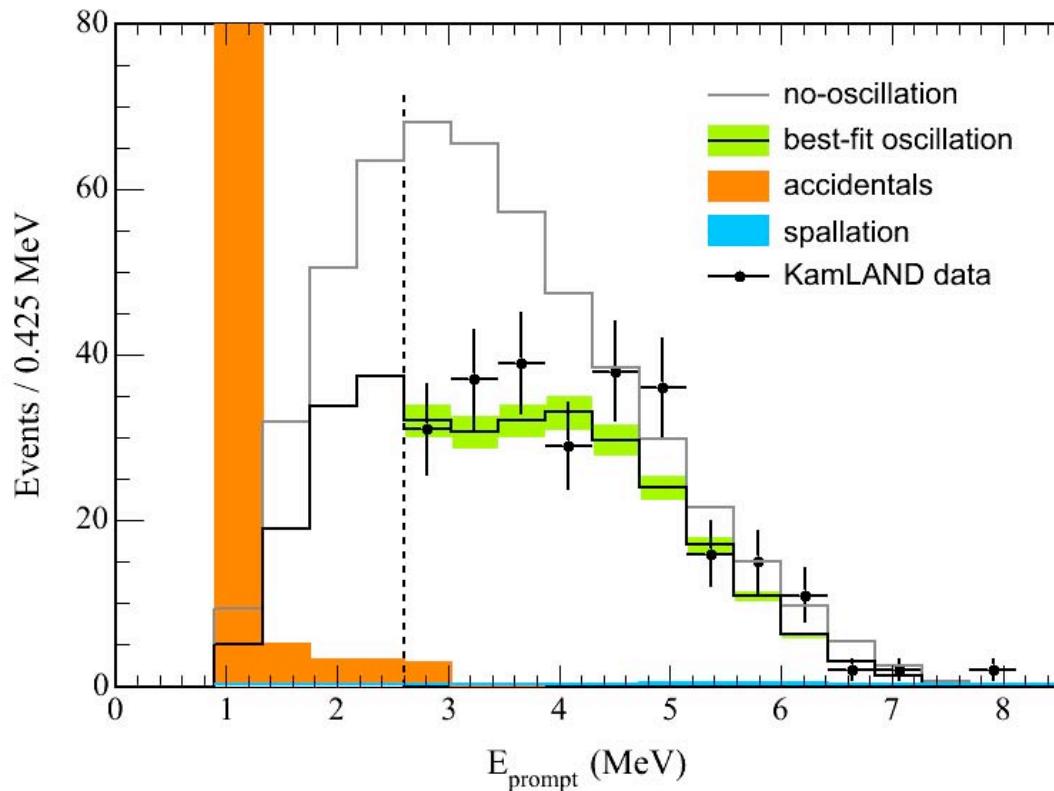
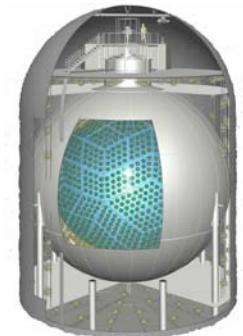
## 50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

1956 “Detection of Free Antineutrino”,  
Reines and Cowan → Nobel Prize in 1995

2003 KamLAND’s observation of  $\bar{\nu}_e$   
disappearance

# KamLAND in 2004: Evidence of Spectral Distortion in Energy Spectrum



hep-ex/0406035 (2004)

Observed $\bar{\nu}_e$	258 events
No-Oscillation	$365.2 \pm 23.7$ (syst.)
Background	$17.8 \pm 7.3$ events
Livetime:	766.3 ton-yr

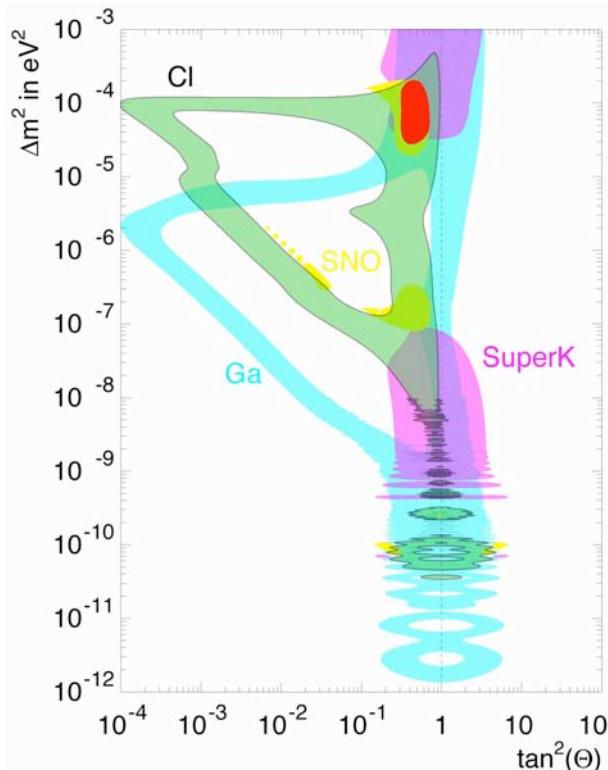
Future: Reduce systematic error  
with improved calibrations.

Spectral Distortions: A unique signature of neutrino oscillation!

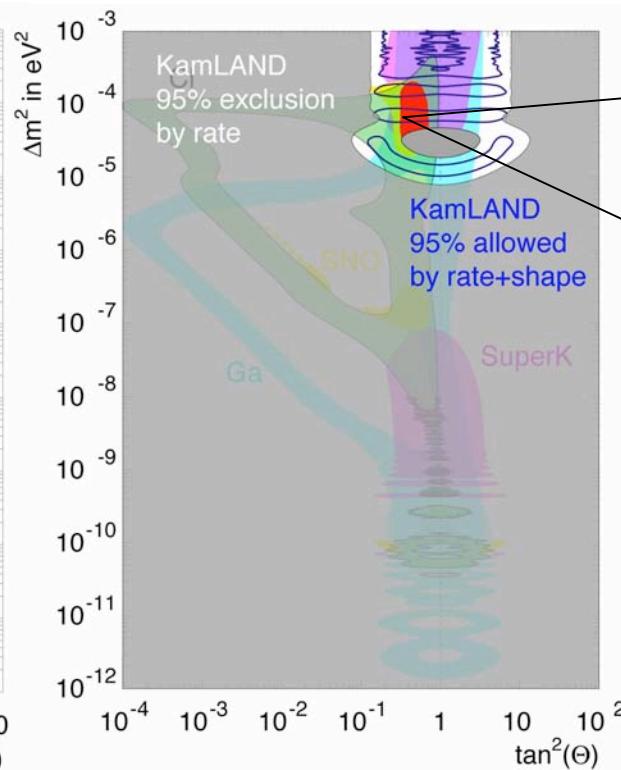
Simple, rescaled reactor spectrum is excluded at 99.6% CL ( $\chi^2=37.3/18$ )

# Measuring Neutrino Oscillation Parameters

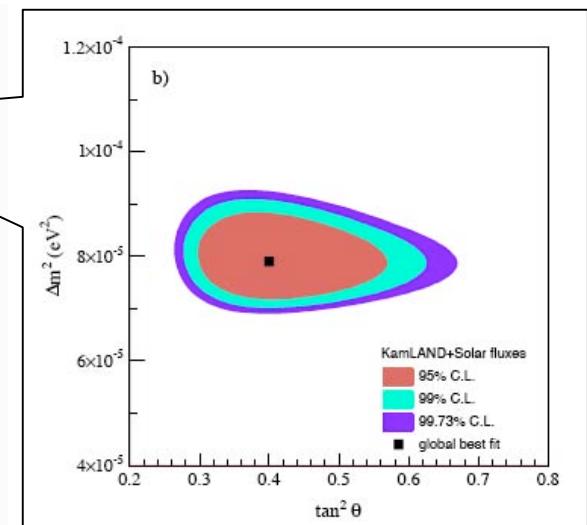
Solar Neutrinos



Solar Neutrinos  
+ KamLAND 2003  
( $\bar{\nu}_e$  rate)



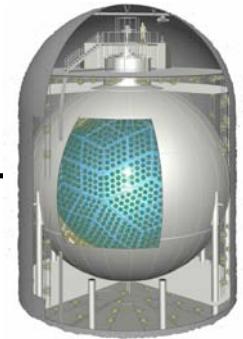
Solar Neutrinos  
+ KamLAND 2004  
( $\bar{\nu}_e$  rate+spectrum)



Agreement between oscillation parameters for  $\bar{\nu}$  and  $\nu$

Precision neutrino physics

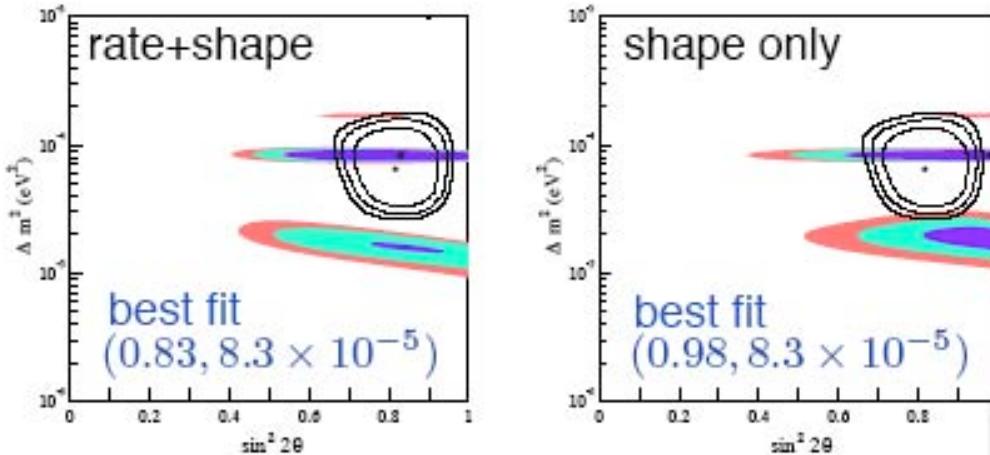
# KamLAND - Systematic Uncertainties



**E > 2.6 MeV**

	%	
Fiducial volume	4.1	• volume calibration
Energy threshold	2.3	• energy calibration or analysis w/out threshold
Cut efficiency	1.6	
Live time	0.06	
Reactor power	2.1	<i>given by reactor company,</i>
Fuel composition	1.0	<i>difficult to improve on</i>
$\bar{\nu}_e$ spectra	2.5	
cross section	0.2	<i>theoretical, model-dependent</i>
<b>Total uncertainty</b>	<b>6.5 %</b>	

# Further Improvements on Systematic Errors

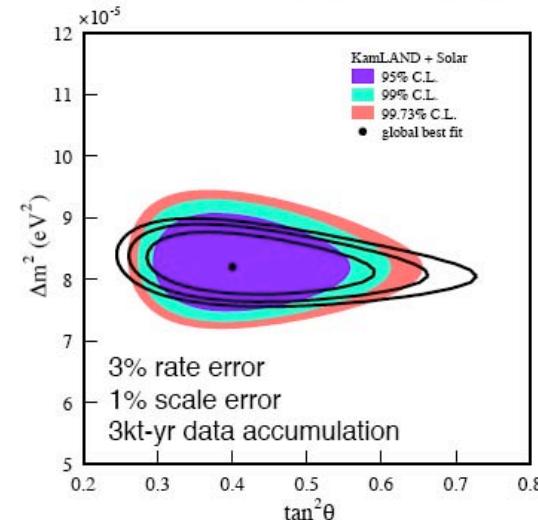


Most constraints from  $\bar{\nu}_e$  spectrum due to systematic error on  $\bar{\nu}_e$  rate

Further improvement on oscillation parameters with reduced systematic errors

KamLAND will make most precise determination of  $\Delta m_{12}^2$  for the foreseeable future.

KamLAND only  
rate+shape sensitivity  
(rough estimation)



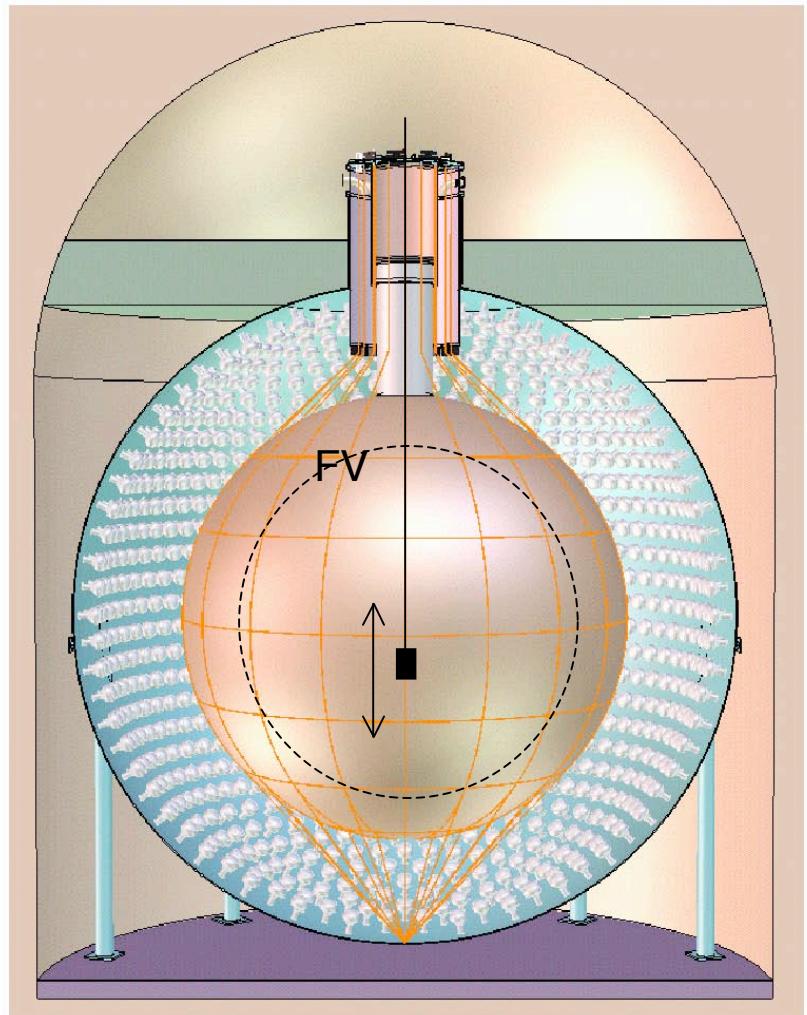
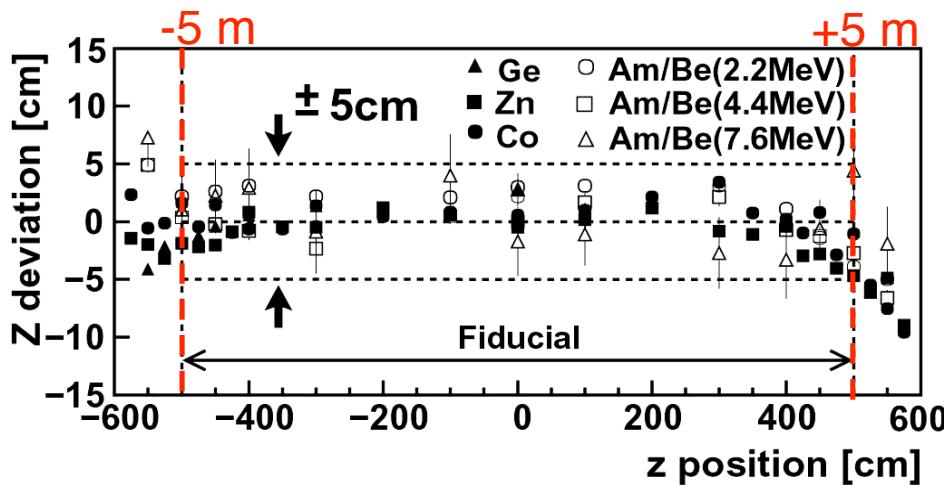
capability to reject full mixing

mixing angle determination comparable with current solar data

# KamLAND z-axis Calibration

## Routine Calibration Sources

$^{68}\text{Ge}$      $e^+$      $2 \times 0.511 \text{ MeV}$   
 $^{65}\text{Zn}$      $\gamma$      $1.116 \text{ MeV}$   
 $^{60}\text{Co}$      $\gamma$      $2.506 \text{ MeV}$   
AmBe     $\gamma, n$      $2.22, 4.44, \text{ and } 7.65 \text{ MeV}$   
Laser and LEDs



$^{60}\text{Co}: 1.173+1.333 \text{ MeV in the detector}$

$$\sigma = 6.2\% / \sqrt{E}$$

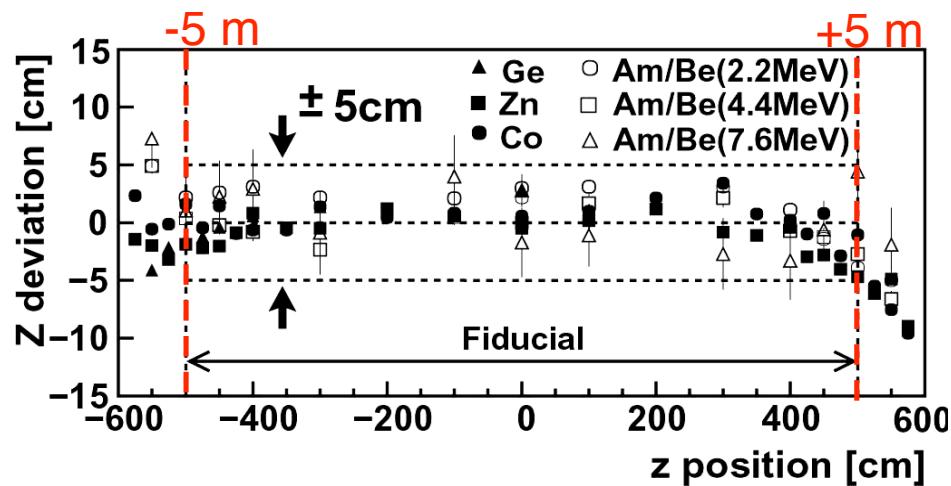
light yield: 239 p.e./MeV

# KamLAND z-axis Calibration

## Routine Calibration Sources

$^{68}\text{Ge}$	$e^+$	$2 \times 0.511 \text{ MeV}$
$^{65}\text{Zn}$	$\gamma$	$1.116 \text{ MeV}$
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AmBe	$\gamma, n$	$2.22, 4.44, \text{ and } 7.65 \text{ MeV}$

Laser and LEDs

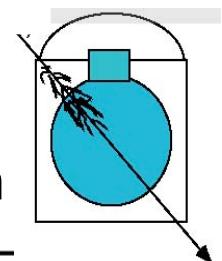
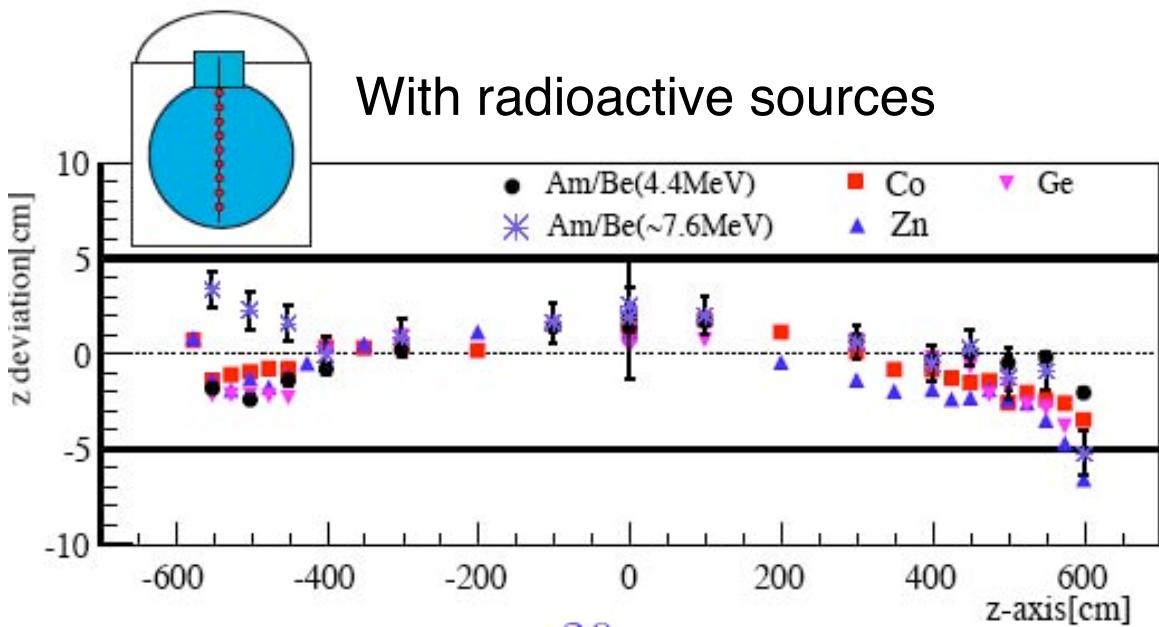
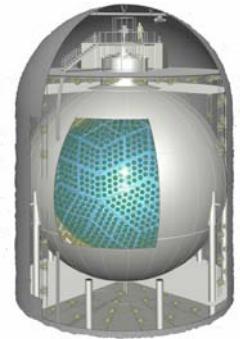


$^{60}\text{Co}: 1.173+1.333 \text{ MeV in the detector}$

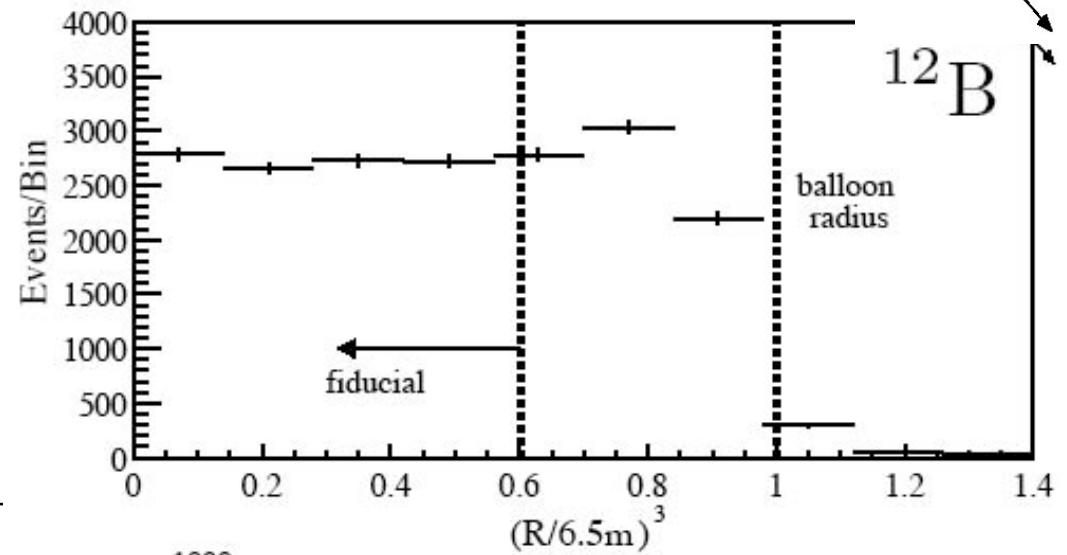
$$\sigma = 6.2\% / \sqrt{E}$$

light yield: 239 p.e./MeV

# Fiducial Volume Determination



With muon spallation



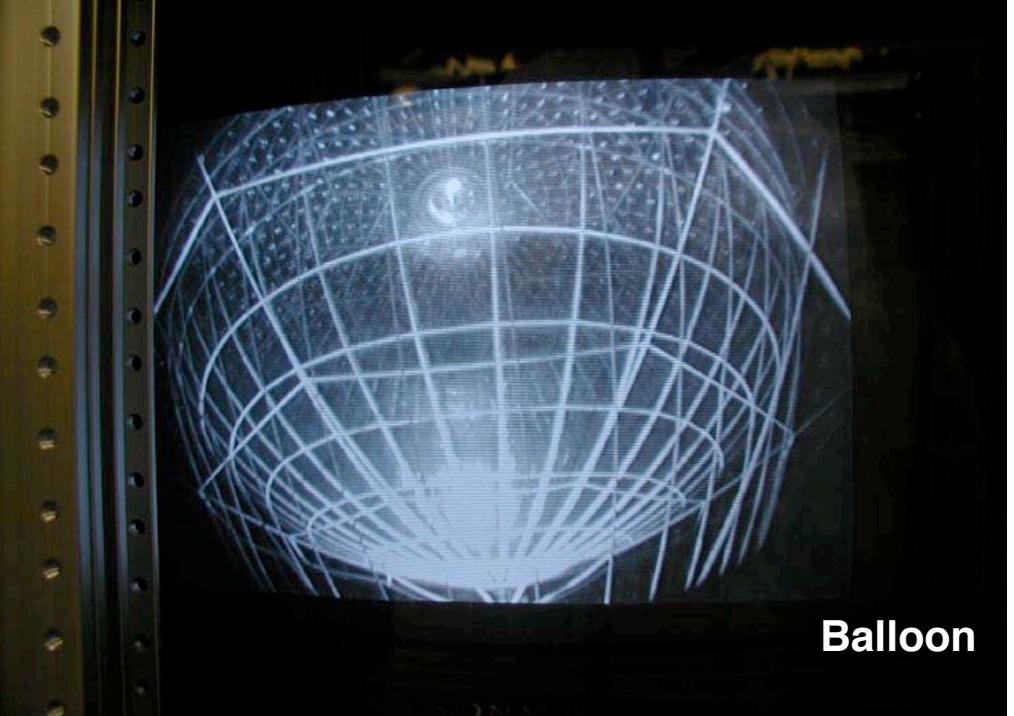
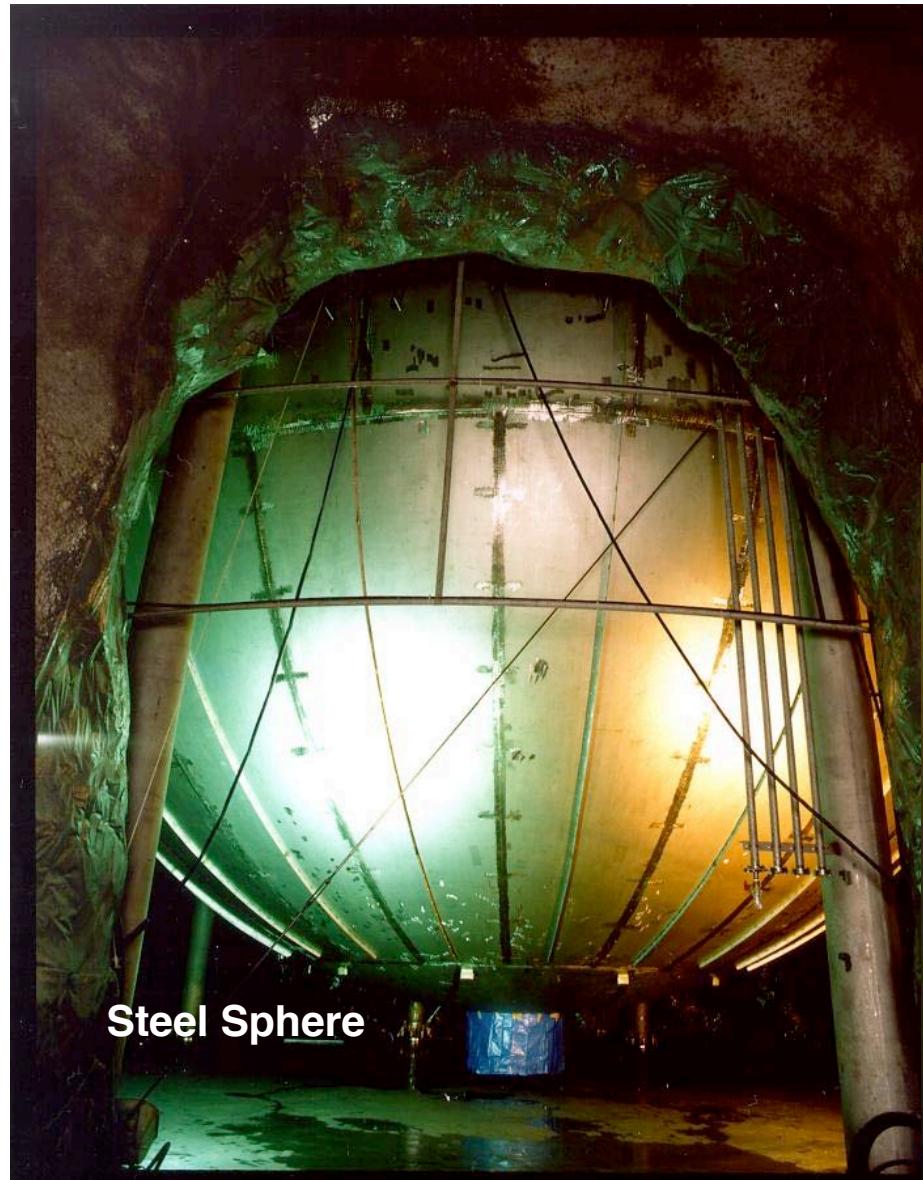
## Fiducial/Total Volume Ratios

Geometrical	$0.595 \pm 0.013$
$^{12}\text{B}$	$0.607 \pm 0.006$
$p(n,\gamma)\text{d}$	$0.587 \pm 0.013$
$^9\text{Li}$ relative	< 2.7%

KamLAND volume error: 4.7%

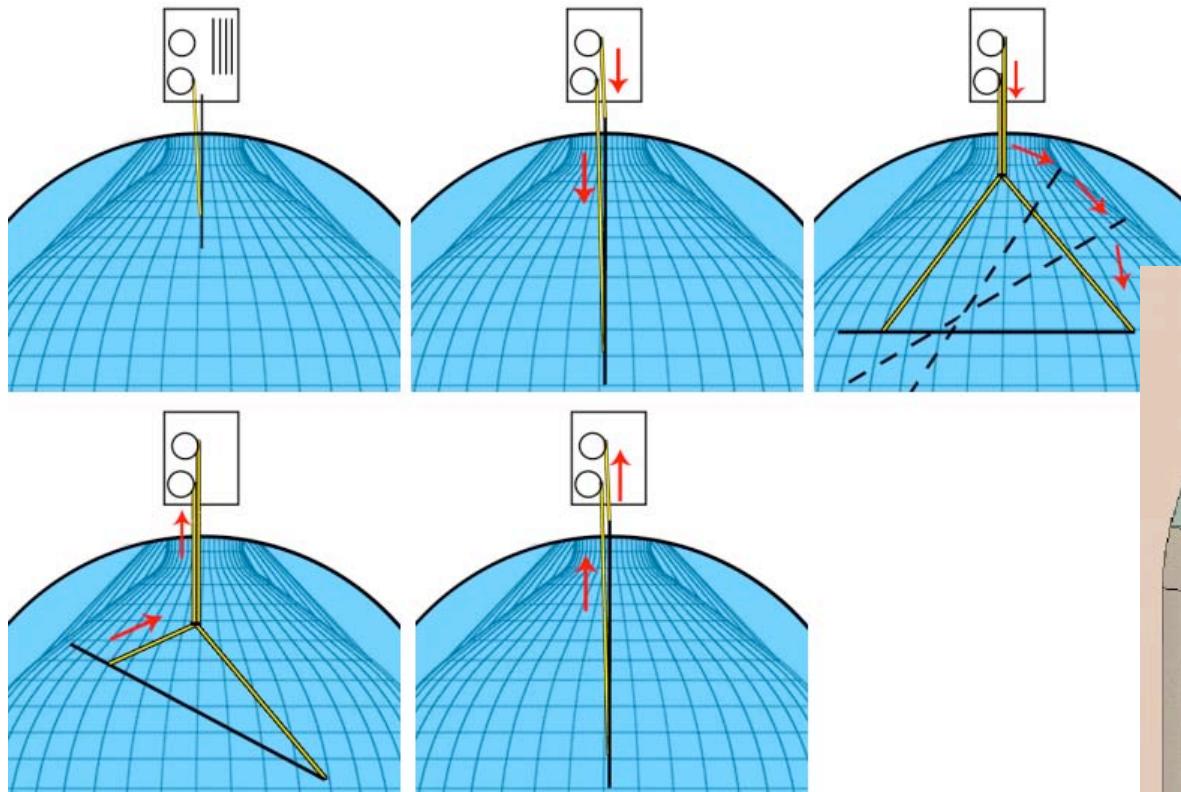
# KamLAND

---



# KamLAND Full-Volume Calibration

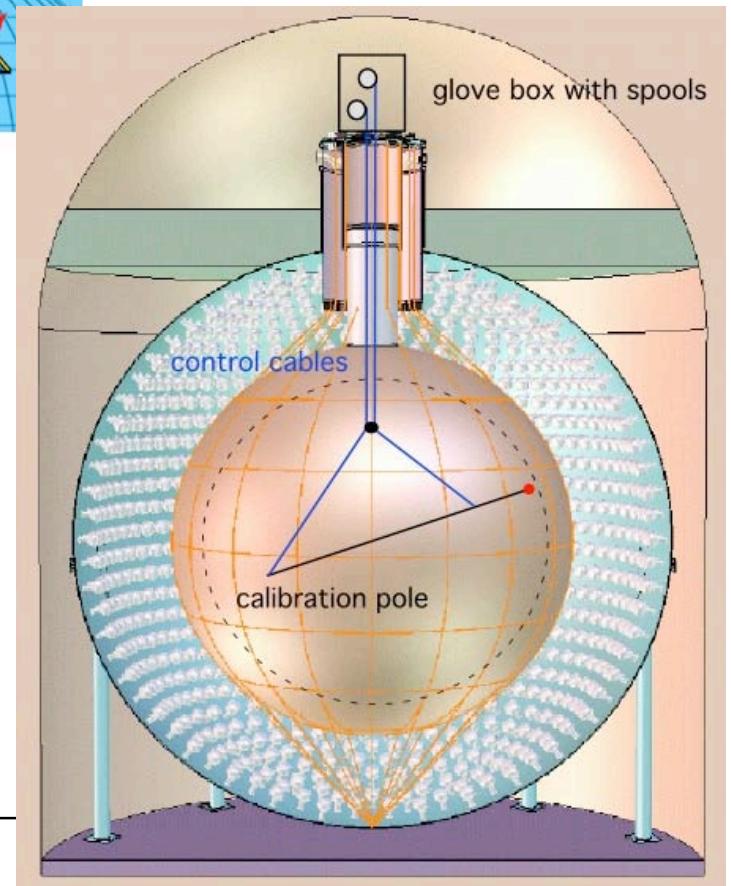
Calibration throughout entire detector volume



Fiducial volume:  $R < 5.5$  m

$$\Delta R_{FV} = 5 \text{ cm} \rightarrow \Delta V = 2.7\%$$

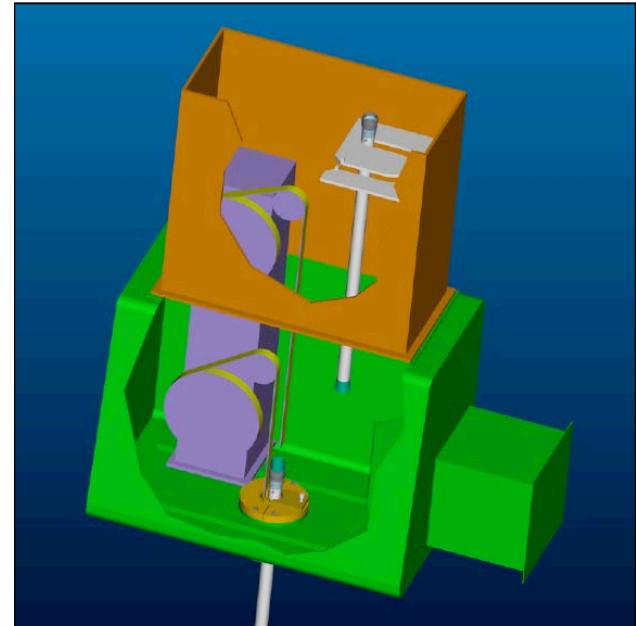
$$\Delta R_{FV} = 2 \text{ cm} \rightarrow \Delta V = 1.1\%$$



Position Dependence of Detector Response

Event energy  
Vertex reconstruction

$$E(r, \theta, \phi)$$
$$R_{fit}(r, \theta, \phi)$$

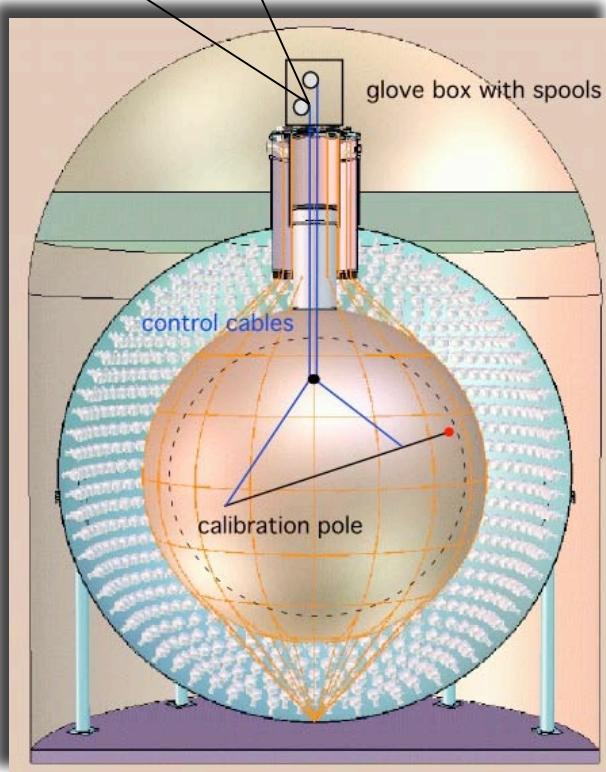


## Construction of a Full-Volume Calibration System

- I. compatible with scintillator
- II. low-background
- III. precise positioning

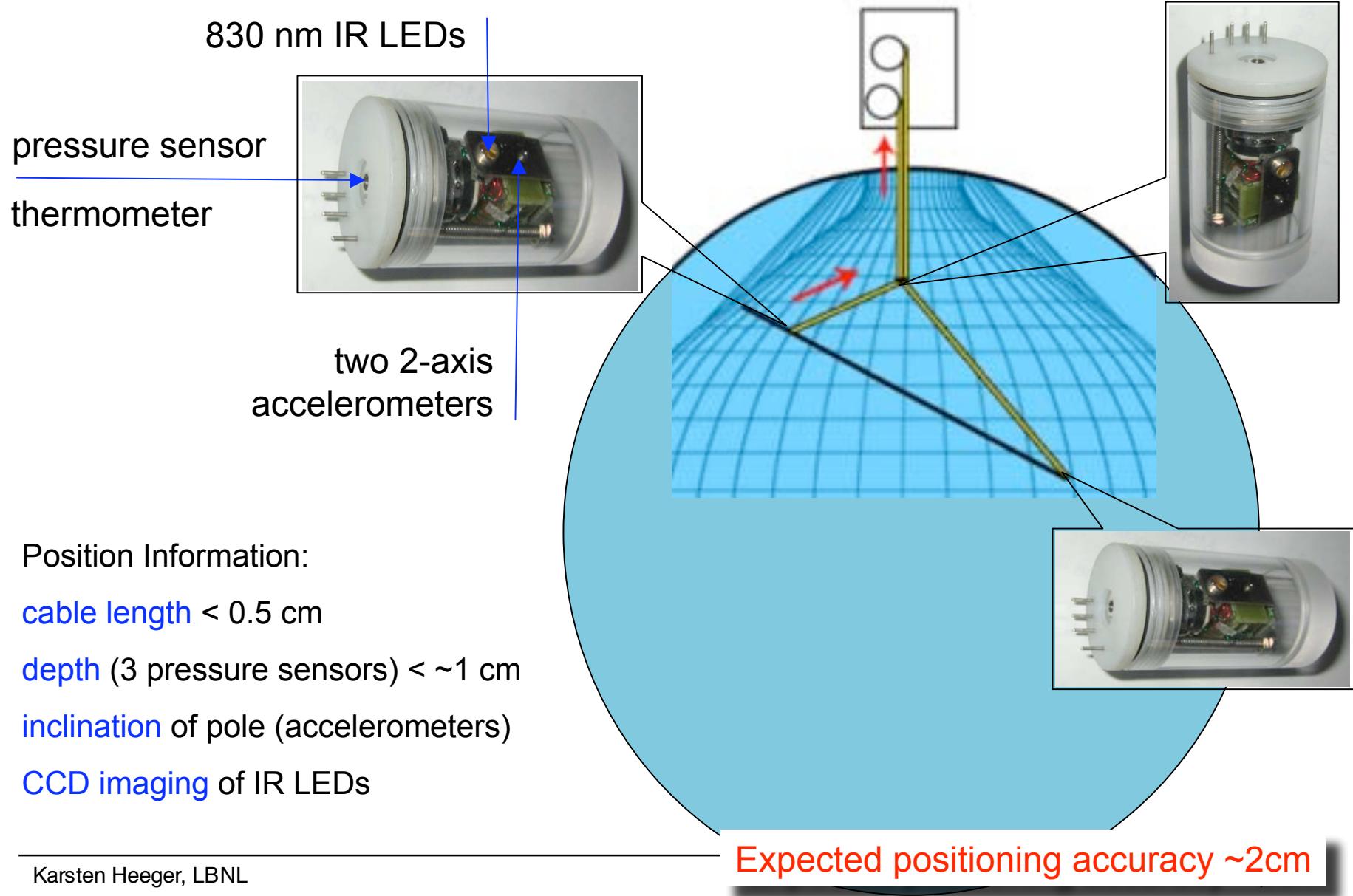


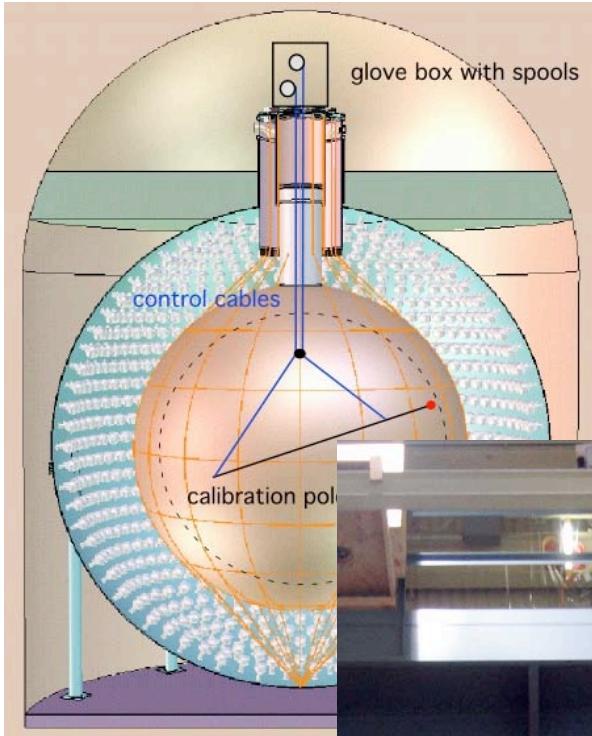
Fall 2003



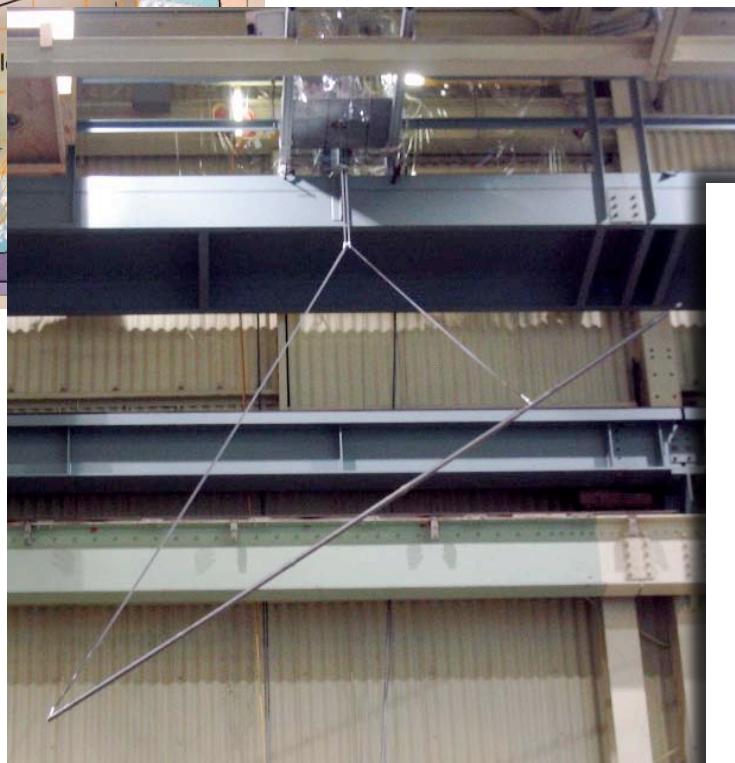
Fall 2004

# Instrumentation of the Calibration System





Designed and built a full-volume calibration system for KamLAND

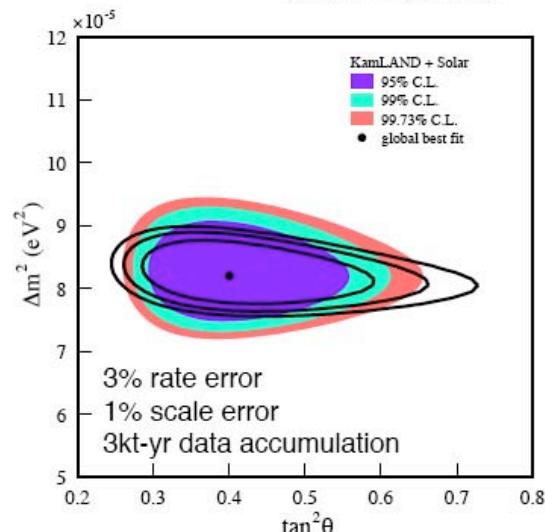


Commissioning in early 2005  
Last major detector upgrade for KamLAND

Will reduce KamLAND's systematic uncertainty on the fiducial volume from 4.7% to 1-2% and improve its sensitivity to  $\Delta m^2_{12}$ .

factor ~2 improvement?

KamLAND only  
rate+shape sensitivity  
(rough estimation)



mixing angle determination  
comparable with current solar data

capability to  
reject full mixing

# KamLAND Collaboration



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